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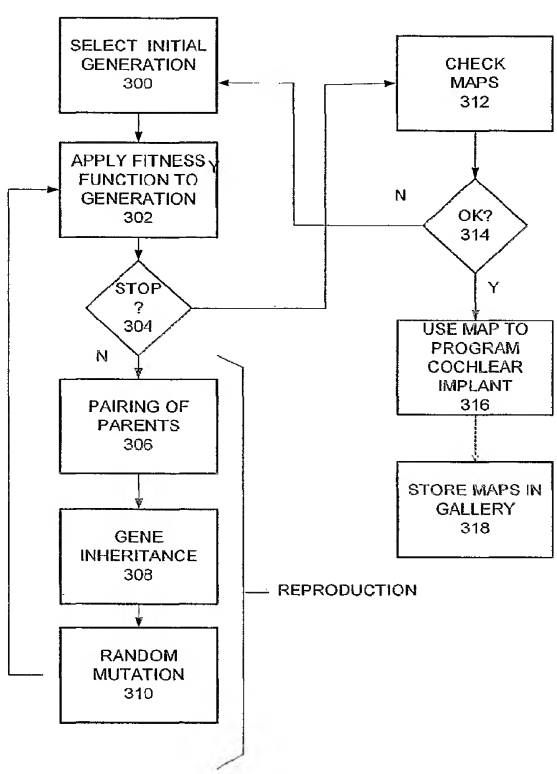
(54) Title: COCHLEAR IMPLANT SYSTEM WITH MAP OPTIMIZATION USING A GENETIC ALGORITHM



(57) Abstract: A method for fitting a cochlear implant to a patient uses a genetic algorithm that operates to generate successive generations of multiple groups of values for a parameter subset, after the selection of an initial generation (300), and patient feedback (302) during execution of the genetic algorithm determines the multiple groups of subset values in successive generations. In each generation, half of the groups of values for the parameter subset are selected and used to determine the groups of values for the next generation. Values for the parameters not included in the subset are selected by any traditional method that does not use a genetic algorithm.

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Cochlear Implant System with MAP Optimization Using A Genetic Algorithm

Field of the Invention

This invention relates to cochlear implants and more particularly to the use of a genetic algorithm in the fitting of a cochlear implant.

Background of the Invention

A. Cochlear Implants

Modern cochlear implant prostheses provide a wide variety of fitting options that can be customized for each individual recipient. At the highest level, one of several stimulation 'strategies' may be selected. Each strategy defines an algorithm for converting acoustic sound input into a sequence of electrical stimuli applied to electrodes within the cochlea. Examples of strategies currently in clinical use are the SPEAK, ACE, CIS and SAS strategies.

Within any given strategy a great many parameters and parameter values may be set to tailor the encoding and stimulation for an individual patient. Examples of parameters and parameter values that may be selected for a strategy are the number of frequency bands (channels) represented, the intracochlear and/or extracochlear electrodes associated with each channel, the pulse repetition rate for each channel, the pulse width for each channel, the number of spectral maxima periodically chosen for representation, the mapping of sound pressure to stimulus current for each channel (thresholds, comfort levels and compression curves), front end filtering of the audio from the microphone (pre-emphasis), and automatic gain control threshold, compression ratio, and attack and release times. (As used herein, the term 'parameter values' refers collectively to values of parameters, whether selectable options are programmed on or off, and in general to any choices that are made during a fitting procedure.)

The ability of a cochlear implant user to understand speech or recognize other sounds depends strongly on the strategy selection and the adjustment of parameters. It is known that no single set of parameters provides an optimal outcome for all users. Users are heterogeneous such that, in general, each user requires a different set of parameters to achieve optimal performance. Parameter values must be tailored to the individual in order to maximize speech reception or user satisfaction.

The task of the clinical professional, usually an audiologist, is to choose a set of parameters – called a 'MAP' -- that will provide the best possible outcome for an individual user. Because there are hundreds or thousands of possible MAPs, it is not practical to try all of the alternatives exhaustively and to evaluate performance of each for an individual user. Nor is it possible to identify an optimal MAP by prescription based upon a limited set of measures as is, for example, the case in fitting eyeglasses or a hearing aid. Optimal fitting of cochlear implants by prescriptive testing has not proved to be consistently successful. Nor is it possible to optimize parameters one at a time, adjusting each in succession to its best value. This is because the parameters interact strongly, and often non-monotonically. For example, increasing stimulus rate may improve the outcome for one set of electrodes, but worsen it for another set.

As a result, clinicians have adopted a variety of approaches for fitting the device parameters to the patient. Some simply fit default parameters to all users. Some adopt preferred MAPs, which they believe are good, if not best, for many or most individuals. These may be based upon personal experience, published performance data, or intuition. Some clinicians evaluate a limited set of alternatives. Some attempt to adjust individual parameters based upon measured perceptual limitations and inferred relationships to fitting parameters. These approaches are time consuming, costly, and unreliable.

The fundamental problem remains that there is no known method for systematically identifying the particular MAP that achieves the best outcome for an individual patient. And this problem is exacerbated each time that manufacturers expand available parameter ranges or introduce new encoding strategies.

In the absence of a prescriptive procedure, an adaptive procedure can sometimes be employed to solve an optimization problem. An adaptive procedure steps through a sequence of solutions with the objective of converging gradually towards the best one. Traditional analytic optimization procedures use current and past measurements of performance to predict, at each iteration, parameter adjustments that will incrementally improve the outcome. But these methods generally fail when there are strong nonlinear and nonmonotonic interactions among parameters as is the case in cochlear implant fitting. They may converge toward a local maximum rather than the absolute maximum, or fail to converge at all. They may also fail when the measurements are noisy, as is often the case when measuring auditory response in humans.

The problem referred to can be appreciated by studying Figs. 1A and 1B. They represent a simple case in which values for only two parameters, on the X and Y axes, must be determined. The vertical (Z) axis represents the 'fitness function,' i.e., how good a result is produced by each X-Y pair of values. In Fig. 1A, the value of either variable can be optimized without radically affecting optimization of the other. There is only one 'hump' and eventually an adaptive procedure will give rise to X and Y values whose fitness function is a maximum, at the top of the hump. But in Fig. 1B, changing the value of either variable affects the optimum value of the other. Once the variable values are situated on a hump, the adaptive procedure may give rise to X and Y values whose fitness function is a local maximum (at the top of the hump), but there may be another hump, with a higher peak, that the variables never even reach. It has been believed that adaptive procedures in fitting a cochlear implant would converge toward a local maximum rather than a global maximum, and that adaptive procedures might not converge at all.

B. The Genetic Algorithm

A genetic algorithm is an adaptive procedure, based on a simple model of biological evolution, which can be used to find optimal solutions to a problem. The procedure implements 'natural selection' (survival of the fittest), 'procreation with inheritance,' and random 'mutation.' Genetic algorithms generally resist convergence on local maxima. The underlying premise is that the evolutionary process will, over multiple generations, produce an 'organism' which is optimal in the sense that it is most likely to survive and procreate.

Each iteration of the genetic algorithm procedure begins with one generation of organisms and produces a succeeding generation. This involves two steps: (1) selection -- choosing a subset of organisms as potential 'parents' of the organisms ('children') of the succeeding generation; and (2) procreation -- creation of 'children' from sets of potential 'parents' (usually pairs).

In genetic algorithms, selection operates on strings of binary digits stored in the computer's memory, and over time, the functionality of these strings evolves in much the same way that natural populations evolve. Genetic algorithms are capable of evolving surprisingly complex and interesting structures. These structures may represent not only solutions to problems, but also strategies for playing games, visual images, or even simple computer programs. The Darwinian theory of evolution depicts biological systems as the product of the ongoing process of natural selection. Likewise, genetic algorithms allow engineers to use a computer to evolve solutions

over time, instead of designing them by hand. Because almost any method, theory, or technique can be programmed on a computer, this implies an approach to problem solving that can be, at least partially, automated by a computer.

The basic idea of a genetic algorithm is that first a population of organisms is created in a computer (typically with genes stored as binary strings in the computer's memory), and then the population is evolved with use of the principles of variation, selection, and inheritance. There are many ways of implementing this idea, but the most basic is that suggested by J. H. Holland, in Adaptation in Natural and Artificial Systems, Univ. of Michigan Press, Ann Arbor, MI, 1975, reprinted by MIT Press, Cambridge, MA, 1992. Each of a group of organisms in a 'generation' is assigned a fitness value by a fitness function. On the basis of these fitness values, the selection phase ranks the organisms. After selection, genetic operators are applied probabilistically; some organisms may have bits in their genes mutated from a 1 to a 0 or a 0 to a 1, and parts of different organisms' genes are then combined into new ones. The resulting population comprises the next generation and the process repeats itself.

The fitness function is the primary place in which the traditional genetic algorithm is tailored to a specific problem. Once all organisms in the population of a particular generation have been evaluated, their fitnesses are used as the basis for selection. Selection is implemented by eliminating low-fitness individuals from the population, and inheritance is often implemented by making multiple copies of high-fitness individuals. Genetic operators such as mutation (flipping individual bits) and crossover or inheritance (exchanging sub-strings of two organisms to obtain two offspring) are applied probabilistically to the selected individuals to produce new organisms. By replacing members of the old generation with such new organisms, new generations are produced either synchronously, so that the old generation is completely replaced, or asynchronously, so that the new and old members of the generation overlap. The genetic operators have been shown to generate new organisms that, on average, are better than the average fitness of their parents. Therefore, when this cycle of evaluation, selection, and genetic operations is iterated for many generations, the overall fitness of the population generally improves, on average, and the organisms in the population represent improved 'solutions' to whatever problem was posed in the fitness function.

Selection can be performed in any of several ways. It can arbitrarily eliminate the least fit 50% of the population and make one copy of all the remaining organisms,

it can replicate organisms in direct proportion to their fitness, or it can scale the fitnesses in any of several ways and replicate organisms in direct proportion to their scaled values (a more typical method). Likewise, the crossover operator can pass on both offspring to the new generation, or it can arbitrarily choose one to be passed on. These and other variations of the basic algorithm are well known in the art.

C. The Genetic Algorithm and Cochlear Implants

The genetic algorithm has been applied to hearing aids, the art closest to that of cochlear implants. The fitness function in this type of case is not based on application of a formula. Rather, the user provides feedback in the form of accepting or rejecting organisms in a population, where each organism is a set of parameter values, or the user ranks the organisms and thus affects which organisms populate the next generation. This variation of the genetic algorithm, involving feedback or interactivity, is discussed in a review article by H. Takagi, Interactive Evolutionary Computation: Fusion of the Capabilities of EC Optimization and Human Evaluation, Proceedings of the IEEE, Vol. 89, No. 9, September 2002., pp. 1275-1296.

The genetic algorithm has not been applied, however, to cochlear implants. Even though there is an extensive literature on the genetic algorithm, including applications with a human observer in the loop and one specifically fitting hearing aids, the task of fitting a cochlear implant is so daunting that most workers did not believe the genetic algorithm could be adapted to cochlear implants. The hearing aid prior art obliged the listener to scale (assign a numerical value to) each member of the population. Even experienced cochlear implant users cannot reliably scale the quality of the percept. The sound sensation varies so much across fittings, and can be disparate in so many ways, that numerical scaling is essentially impossible. So all prior art using scaling in the evaluation function is impractical for the cochlear implant task. This is even more of a problem with naïve (newly implanted) users, to whom all of the percepts are foreign. Even ranking without scaling would be difficult for new users.

Moreover, the complexity of the fitting (the number of parameters to be adjusted) would demand too many bits in each population member. With many bits, the number of members per population must be high, and that would swamp the user with choices to evaluate. This is both impractical in time spent, and impossible for the listener who cannot reasonably compare many simultaneous options.

Summary of the Invention

In the invention, a cochlear implant is at least partially fitted to a patient by executing a genetic algorithm to select values for a subset of all the parameters for which values must be selected to fit the implant. The genetic algorithm operates to generate successive generations of multiple groups of values for this parameter subset, and patient feedback during execution of the genetic algorithm determines the multiple groups of subset values in successive generations. Selection is thus based on the subjective listening judgment of the patient during execution of the genetic algorithm. In each generation, substantially less than all (e.g., half) of the groups of values for the parameter subset are selected and used to determine a larger number of groups of values for the next generation (e.g., twice as large, if it is desired that all generations be of the same size). Values for the parameters outside the subset are selected by any traditional method that does not use a genetic algorithm. In fact, what makes use of a genetic algorithm practical in a cochlear application is that most of the parameters are not selected by using a genetic algorithm. In one illustrative embodiment of the invention, there are only three parameters in the subset that are selected by a genetic algorithm – parameters relating to rate, number of channels and filtering characteristics. These are the characteristics that many clinicians feel are the most important in the fitting process.

The patient feedback involves selecting preferred groups of parameter subset values in one generation ('survivors') from which the groups of parameter subset values in the next generation are determined, but preferably groups of subset values are not ranked. They are selected for use in deriving the next generation or they are not selected, but the patient does not rank groups of subset values from best to worst. With eight groups per generation, for example, the patient simply has to choose the four he likes best.

Preferably, as discussed above, the values of the subset of parameters are represented by a MAP consisting of binary string of, for example, 6-12 bits. It is also best that there be 6-12 MAPs in each generation, with 8 MAPs or groups being used in the illustrative embodiments of the invention.

In the examples to be discussed in detail below, a set of parameters is assigned to the MAPs. The string of bits of the MAPs may be divided into separate sub-strings each of which represents the value of a respective parameter. Alternatively, each different valued string may simply identify a respective subset of parameter values without specific bit positions in the string being associated with

particular parameters. In this latter arrangement, a lookup table is used to relate parameter values to specific MAPs. Alternatively, a combined approach may be used with some of the bits in the string divided into separate sub-strings each of which represents the value of a respective parameter, and the others of the bits in the string identifying respective pre-selected parameter subset values by a smaller lookup table.

The parts of strings of bits that are combined to form an offspring may be cut from parent strings at positions that separate parameter values (if separate sub-strings represent the values of respective parameters). The strings may be cut at positions that do not vary from generation to generation, or they may be cut at positions that do vary, even randomly, from generation to generation. In the illustrative embodiment of the invention, the genetic algorithm is executed a fixed number of times, e.g., 15, to generate a fixed number of successive generations of multiple groups of values for the parameter subset, and a final group of values for the parameter subset is selected from the groups in the final generation. However, alternative stopping criteria may also be used.. Examples of alternative criteria are ones based upon a measure of homogeneity within generations, or a measure of consistency of the listener's judgments. In addition, a record may be made of any group of values for the parameter subset that the patient identifies as satisfactory in any generation, and a final group of values for the parameter subset may be selected from the groups in the final generation and those previously identified by the patient.

As in traditional applications of genetic algorithms, successive generations of multiple groups of values for the parameter subset can be determined in part by mutations. Preferably, in each generation the probability of each bit in a string of bits mutating is fixed for all bits, e.g., at between 1% and 10%, with 3% being preferred. (It is possible for the clinician or even the patient to vary the mutation rate as the algorithm is executed. Similarly, depending on the progress of the algorithm, it is possible for the algorithm to change its own mutation rate.)

The multiple groups of values for the parameter subset that are used in the first generation of the execution of the genetic algorithm may be based on predetermined clinician judgment. Alternatively, the multiple groups of values for the parameter subset that are used in the first generation of the execution of the genetic algorithm may be random.

Broadly speaking the invention is a method of fitting a cochlear implant to a patient that comprises the steps of forming a set of digit sequences, each sequence

representing a respective set of parameter values for the implant. The implant is tested on the patient using the parameter values represented in the sequences and the sequences that provide superior performance are selected. Parts of the selected sequences are then combined to form new sequences. The testing, selecting and combining steps are then iteratively repeated to derive a final sequence for use in fitting the implant.

Brief Description of the Drawings

Further objects, features and advantages of the invention will become apparent upon consideration of the following detailed description in conjunction with the drawing, in which:

Figs. 1A and 1B, discussed above, help explain why it has been believed that adaptive procedures in general, and a genetic algorithm in particular, could not be used to fit a cochlear implant;

Figs. 2A-2E depict successive steps in the performance of the genetic algorithm for a specific generation (generation 5 in the example) in accordance with the principles of the invention;

Fig. 3A depicts how specific bits in any bit string can represent values of respective parameters in the first illustrative embodiment of the invention;

Fig. 3B illustrates how two 'parents' reproduce;

Fig. 3C shows how only 4 of the 8 organisms in generation N survive, and how they then reproduce and give rise to 8 organisms in generation N+1, and Fig. 3D shows a flow chart for the determining a MAP using a genetic algorithm;

Figs. 4-6 depict show the three different ways in which a MAP formed of a bit string can represents parameter values;

Fig. 7 shows a table of seven parameters that can be determined using the subject algorithm, and the possible values of each of the parameter;

Fig. 8 shows a partial listing of 10-bit maps used to determine the parameters of Fig. 7; and

Fig. 9 shows a partial listing of frequency allocations to various channels to illustrate FAT shifting;

Detailed Description of the Preferred Embodiments

There will first be described some of the terms used in connection with genetic algorithms and, in some cases, how these terms are applied to genetic algorithms for fitting cochlear implants in accordance with the invention.

In a genetic algorithm, an 'organism' is entirely defined by a set of N_b 'genes' (bits). The number of possible unique organisms is 2^{Nb}. In the invention, the organism to be optimized is a cochlear MAP (values for a set of parameters). In the example of Fig. 3A, N_b is 8 so a MAP is defined by a gene set or string of 8 bits forming 256 possible MAPs. Each of the 8 bits may be used to designate several parameters for a cochlear implant. In the example shown in Fig. 3a three such parameters are designated. Three bits are used to select a stimulus rate (the rate, in Hz, at which high-energy channels are selected and stimulus pulses are delivered to groups of N electrodes), three bits select spectral maxima counts (the number N of electrodes periodically selected to be stimulated, representing the N frequency bands with the highest energy at the time), and the remaining two bits select 1 of 4 channel counts (the number M of channels, or frequency bands, used to represent the sound spectrum, periodically, electrodes whose corresponding channels have the highest energy are selected to be stimulated). Other parameters are assumed to be constant or derived from one of the three represented parameters; they are fitted using traditional methods. As discussed in more detail below the number of bits for each MAP and the number of parameters defined by the MAPs can be different.

In a genetic algorithm a 'generation' can be considered to be a set of organisms. Generally, the number of organisms N_g is constant from generation to generation. In a first embodiment of the invention, the initial generation comprises a selection of 8 different MAPs as illustrated in Fig. 3A, which span the parametric ranges. These MAPs can be completely random. Alternatively, some or all MAPs of the initial generation may be the preferences of clinicians, or may be selected from the results of a previous execution of the method, as discussed in more detail below.

A 'fitness function' is used to evaluate each of the organisms in each generation. The fitness function identifies the organisms that will survive to become parents and procreate and the organisms that die. Generally, the number of survivors is constant from generation to generation. In one embodiment of the invention, a fitness function is used that causes half of the organisms survive. Preferably the fitness function is a subjective listening test performed by the user. He or she listens to speech presented through each of the MAPs in a generation, and

selects half of the MAPs that produce the best intelligibility. Alternatively, the fitness of a MAP may be determined entirely, or in part, from objective measures, i.e., measurements not involving a judgment by the listener, such as cortical or brainstem evoked potentials measured from the listener, the listener's ability to repeat a speech token, the quality of a the listener's speech while listening to his own speech with the MAP, results of an objective speech reception test, or expert knowledge about known beneficial parameter combinations.

'Reproduction' involves three separate operations: pairing of parents, inheritance, and mutation. For example, Fig. 2A depicts some arbitrary generation in an overall sequence (generation 5 in the example) that has evolved to contain 8 organisms or individuals. The 'fitness function' rejects four of these (circled organisms are those being rejected), as shown in Fig. 2B, with Fig. 2C showing the survivors. The survivors are then paired, as shown in Fig. 2D, with each survivor mating with two others. Each pair produces two children. The 8 children make up generation 6, as shown in Fig. 2E.

In the illustrative embodiment of the invention, a round-robin algorithm is used to identify pairs of parents in each generation. Each pair produces several children. In the preferred embodiment, each pair produces two children. For example, 8 MAPS can be arranged into four pairs of parents resulting in a new generation of 8 children. Each child inherits some of its 'genes' from each parent. For example, the string of bits of each MAP can be partitioned by boundaries into sub-strings that constitute 'genes'. Finally, after reproduction, each gene is, optionally, subject to random inversion (mutation). Preferably the probability of each mutation is small. Typically this probability may range from 1 to 10%. In a preferred embodiment, the mutation probability is 3%.

The genetic algorithm consists of performing reproduction on an initial generation several times, and then using the last or final generation to program a cochlear implant. This process is now explained in detail in conjunction with the Figures.

Fig. 3A shows how an organism represented by the leftmost circle in Fig. 3A and corresponding to the circles in Figs. 2A-2E. The organism in this example is a MAP defined by a set of 8 binary genes. In this case, the string of 8 bits has been partitioned into three sub-strings, each sub-string corresponding to a parameter. The first 3 bits set represents 1 of 8 stimulation rates, the second 3 bits set represents 1 of 8 maxima counts, and the 2 bits set 1 of 4 channel counts. For each of the 8

stimulation rates, a corresponding set of threshold (T) and comfort (C) levels, one for each electrode, is also selected. Ts and Cs are determined by clinician measurement at the corresponding rate, or by inference, using a mathematical loudness model, from Ts and Cs measured at a single standard rate. For each MAP appropriate T and C levels are used for each stimulation rate.

Initially, (step 300 in Fig. 3D), a generation of eight MAPs is selected. Initialization requires the selection of first generation of designs. This selection may be performed by selecting at random from among the set of possible MAPs. Preferably, in order to insure that this initial MAP set has a sufficient measure of heterogeneity, its diversity is computed. Diversity is defined as the average Hamming distance between the various MAPs and it ranges between 0 and 1, with 1 indicating maximum diversity and 0 indicating minimum diversity. If the diversity is below a threshold, for example, 0.53, then the initial generation has an insufficient diversity, and a new set of MAPs is selected.

Moreover, pre-selected MAPs may also be included among the MAPs of the first generation. These pre-selected MAPs may be drawn from prior runs of the fitting procedure, MAPs from the implant patient's gallery or MAPs selected by a clinician based on his experience, suggestions and recommendations from others, etc..

Next, in step 302 the fitness function is applied to the initial generation. That is, the parameters corresponding to the eight MAPs are sequentially programmed into a cochlear system emulator and then tests are performed to determine which subset of the generation provides better results. As discussed above, these tests may be subjective tests based on the perception of the patient, objective tests during which some physiological measurements are taken, or a combination of both types of tests.

For example, as part of the fitness function, the patient is asked to listen to speech token for each of the eight MAPs. The patient can listen to each token as many times as he wants. The tokens are selected from a library of relatively long audio files (e.g., 2 minutes). Each file in this library can consist of a single speaker reading aloud from a newspaper or a passage from an audio book. In one embodiment of the invention, the patient listens to the whole file. In another embodiment, the file is partitioned into shorter segments of random lengths. Each segment is then used as a speech token.

Alternatively, a library of tokens is provided, each token corresponding to a relatively short audio file. A large number of different types of audio files is provided. The diversity between the files is used to explore how different MAPs process the files under common conditions. Each file is played in its entirety and can have predetermined lengths (e.g., four seconds). The library may include separate male and female TIMIT sentence audio files. For example, the library could include 192 sentences from 64 different speakers (3 files per speaker) the speakers being male or female and having various accents or dialects. Preferably, each audio file incorporates a rich range of phenomenes and contextual cuing.

Additionally, long or short audio files within either a noise environment or from speech in babble (BKB) sentences can be used as tokens.

The right side of Fig. 3C shows the 8 MAPs of a generation N. During step 302, the patient determines which 4 of the 8 MAPs are the clearest, in the sense that they are more preferred by the patient. In this manner, four of the MAPs are eliminated as indicated in Figure 3C by the large X. The remaining MAPs are designated as MAPs A, B, C and D. These MAPs are used for reproduction as discussed before.

Next, in step 304 a test is performed to determine if the algorithm should be stopped. In one embodiment, the algorithm is stopped after a predetermined number of generations. In another embodiment, the diversity of the surviving MAPs is compared to a threshold. If the diversity is below a limit (e.g., 0.1) then the surviving MAPs are the final MAPs that are processed as discussed below. Otherwise the algorithm continues with reproduction.

Reproduction consists of three steps: pairing, inheritance and mutation.

Pairing occurs in step 306. As part of this step, each surviving MAP forms pairs with some of the other surviving MAPs. In Fig. 3c, each MAP is paired with two other MAPs, forming four pairs are AB, BC CD and AD. Of course other pairs are possible as well.

The pairs of step 306 are used to generate two children or offsprings in step 308. Fig. 3B shows how an offspring inherits some genes from each parent. For this purpose, a boundary or cutpoint is made in the bit string of each MAP, for example, in the middle. In Fig. 3B, the child MAP includes the first 4 bits of the Mother MAP (for example MAP A) and the last 4 bits of the Father MAP (MAP B).

Thus, in step 308, generation N+1 results from the pairings of step 306, using predetermined criteria. This process is further illustrated on the right side of Fig. 3c. The cut points govern inheritance of genes from each parent and are illustrated by the vertical dotted lines through each child on the right. Genes to the left of the cut point come from one parent, and genes to the right come from the other parent. In the illustrated example, the cut point is allowed to vary randomly across pairings. Alternatively, the cut points can be made in the same position for all the pairings.

As discussed above, in the preferred embodiment of the invention, two children result from each pairing. The genes of each child may be selected from the genes of the parents in different ways. In one embodiment, the genes of one child include the genes from the left side of the cut in one parent and the genes from the right side of the cut from the other parent (as illustrated in Figs. 2B and 2C). The genes for the other child are selected by copying the genes on the right side from the first parent and the left side from the second parent. Bits common to both parents are repeated.

More specifically, in Fig. 2C, each child is identified by a notation such as CD5. The first letter represents the organism in generation N that contributes leftmost bits to the child in generation N+1, the second letter represents the organism that contributes rightmost bits, and the numeral represents the position of the cuts.

Lastly, as part of reproduction, a mutation is performed in step 310. Mutation is implemented by inverting some of the bits of at least some of the children in an arbitrary and random manner. For example, in Fig. 3C, the last or least significant bit in the sixth child of the new generation N+1 is inverted.

Once the new generation N+1 is formed, the fitness function is applied again in step 302 and the process continues.

The four final MAPs found in step 304 are checked further in step 312 to insure that their parameters are acceptable. In other words, a check can be performed to determine if the maps are valid, permissible, admissible or even realistic. If these final MAPs are not acceptable in step 312 then they are returned to the genetic algorithm. Alternatively, a different initial generation is selected in step 300 and the genetic algorithm is repeated. Alternatively, step 312 can be omitted.

If the final MAPs are found acceptable in step 314 then one of them is selected and used to program the cochlear implant system. It has been found that after several iterations, the MAPs become very similar and, therefore, from a

practical point of view, any one of the MAPs may be used. Alternatively, all the MAPs may be presented to the patient and the patient may be allowed to select the MAP that seems to perform best.

The 8 bits that represent a unique MAP give rise to 256 possible different bit strings that represent 256 unique MAPs. Several methods may be used to correlate each MAP to a corresponding set of parameters. Three such methods are discussed below.

Lookup Table (LUT) of Maps

With this method, illustrated in Fig. 4, 256 predetermined maps are chosen. Each may represent any arbitrary admissible combination of parameters. For example, 256 different combinations thought to be useful by expert clinicians could be selected. The only constraint is that each combination be admissible and unique, i.e., no two maps may represent the same combination of parameters. A lookup table associates each of the 256 possible bit strings with one of the 256 available MAPs. Therefore, when a bit string is specified, it uniquely represents a single MAP. With this method, each parameter can have any legal value in each MAP. For example, each of the 256 possible MAPs might have a different rate. In the embodiment illustrated in Fig. 4, five parameters are varied within the set of 256 MAPs. Various, but not all, combinations of the following parameters are constructed within the set of 256 possible maps (some of the possible combinations are not valid clinically and are rejected): (1) Stimulation rate (one of 250, 720, 1200, 1800, or 2400 Hz); (2) number of electrodes used (either 10 or 22); (3) number of maxima per stimulus frame (one of 4, 6, 8, 10, 12, 16, or 20); (4) steepness of output compression (known as the "Q" factor for an ACE or SPEAK map - either 20 or 30); and (5) combination of input audio filtering options (flat, high cut, low cut, or high and low cut). None of these parameters need to be individually represented by any particular subset or sub-string within the 8-bits.

Parameter-Specific Fields

With this method, shown in Fig. 5 (and Fig. 3a), the bit string is broken down into sub-strings or fields. The sub-string in each field is then used to select a particular parameter for the MAP. In the example of Fig. 5, one 3-bit sub-string selects one of 8 possible rates for the MAP. A second 3-bit sub-string selects one of 8 possible channel counts, and a third 2-bit sub-string selects one of 4 possible

filtering options. In this example, each sub-string is contiguous. However, this is not necessary, because there is no significance to the order of the bits in the bit string.

With this method, the available options for any given parameter are fixed by the number of bits in the corresponding sub-string. In the example of Fig. 5, only 8 different rates are available. No MAP can be defined with a rate of 792 Hz, for example, because this rate is not one of the 8 available alternatives.

Combination of Parameter Fields and Lookup

This method, depicted in Fig. 6, is a combination of the previous two methods. One or more sub-strings are defined to select corresponding parameters as in Fig. 5. The remaining bits are used to choose from a table of arbitrary combinations of the remaining parameters. In the example of Fig. 6, one 3-bit sub-string selects one of 8 possible rates. The remaining 5 bits are used to choose, from a lookup table, one of 32 arbitrary combinations of channel count and filtering. As with the first method, each of the 32 arbitrary combinations must be legal and unique.

Lookup Table (LUT) of Maps with 10 bits

As previously discussed, the number of bits per MAP is not limited to 8. If more then 8 bits are used, the process can be used to optimize more parameters. In an alternate embodiment of the invention, 10-bit MAPs are used to optimize seven parameters: the five original parameters discussed above in conjunction with the 8-bit MAPs and two new parameters, FAT shift and T-level bump. These two parameters are described in more detail below. The seven parameters and their allowable values are shown in Fig. 7.

Fig. 8 shows a listing of the first three binary MAPs used to determine the seven parameters of Fig. 7 and the respective parameter values. Some of these values are arbitrary numerical values. For example, a '1' for the FAT shift or the T-level bump designates the default value. '1', '2' and '3' for the filters designate the Low B, Low cut and high cut settings for the filters. Of course, the assignation of each set of parameter values to any 10-bit MAP is arbitrary.

It is well known in the art that a cochlear implant applies stimulation signals to the aural nerves of a patient using a plurality of electrodes. The electrodes are paired to define channels, each channel being used to apply signals corresponding to certain audible frequency bands. Typically, a cochlear system may use up to 23 channels and during the fitting of a cochlear implant a table is designated for the

system that defines the number channels to be used and the frequency band allocated to each channel.

Traditionally twenty seven tables are used to define up to 22 frequency bands corresponding to 22 channels. Fig. 9 is a partial listing of standardized frequency allocation tables (FATs) 6, 7, 8, 14, 15 and 16. Each table lists the upper frequency boundary of each band. The left column of Fig. 9 provides a frequency band index that identifies the rows of the listing. The rows of Table 6 indicates one possible frequency allocation for all frequency boundaries starting at 188 Hz for band 0 and ending with 7938 Hz for band 22. In fact, starting with table 6, the top frequency for the first channel is always allocated frequency 188 Hz and the top frequency for the last channel is always allocated 7938 Hz. Tables 1-5 have been omitted and contain slightly different frequency allocations to the 23 channels. Table 8 indicates the frequency allocation when 21 channels are used. Table 15 shows the frequency allocation for 14 channels. As can be seen from Fig. 9, as the number of utilized channels is reduced, the frequencies allocated to the highest channels are compressed. As a result of this compression, tables with lower number of channels provide a lower resolution of the audible signals at the high frequency ranges.

In the present invention, when the FAT shift parameter is set to its default value, the FAT tables of Fig. 9 are used. When the FAT shift is enabled, the tables are shifted to the left by a predetermined number of columns. In the preferred embodiment, FAT tables are shifted by one or two columns. For example, if table 8 is designated with 21 channels and the FAT shift is set at the default value then the frequency allocations shown in Fig. 9 for table 8 are used. If the FAT shift parameter is at a shift value, then the frequency values of the first 21 channels of table 6 are used. Thus for no shift, the channel 20 is designated the frequency 7938 Hz. When the shift parameter is 1, the channel 20 is designated 6063 Hz. For table 16, with no FAT shift, the channel 12 is designated the 7938 Hz frequency. With shift, table 15 is designated with channel 12 being allocated to 6313 Hz. The tradeoff is that the audible signals above the frequency allocated to channel 20 (for table 8) or channel 12 (for table 16) are lost.

Two other well-known programming parameters in cochlear systems are the T and C (threshold and comfort) levels. The T-level bump pertains to a feature of the invention wherein the T level is raised by a predetermined ratio (for example, 10-20% of the range between the original T and C levels). This feature improves the sensitivity of the system to soft sounds

In addition, in the preferred embodiment, the filters parameter is augmented to include low B (low frequency boost), low C level and high C level. These parameter choices reduce the C level at low and high frequency, respectively.

Because not all combinations of parameter values are possible, only 1032 MAPs are required for the parameters shown in Figs. 7 and 8. Since 10 bits can only define 1024 MAPs, eight combinations of parameter values are arbitrarily excluded.

A genetic algorithm has several properties that make it appealing for optimization of cochlear implant fitting. It is resistant to convergence upon local maxima, it is robust and can tolerate a noisy, inconsistent, or non-linear fitness function (e.g., subjective judgments by the user), it can incorporate 'expert knowledge,' and it is easily automated. Although less than all of the following can be specified in a practical application of the invention, a complete implementation for MAP optimization may include the following:

1) The choice of N_b ;

2) The method for defining a MAP from a set of N_b bits (or, more generally, a set of genes);

3) The number of MAPs per generation N_g ;

4) Initialization – the method for defining the MAPs in the initial generation;

5) Fitness function – the mechanism for selecting survivors

6) Pairing operator – determines the number of parental pairs per generation, the method for selecting them, and number of children per pair (it is possible to implement a system in which children inherit genes from more than two parents)

7) Inheritance operator – the method for determining which of a child's genes come from each parent (the cut point);

8) Mutation operator – the method for randomly determining which genes of a child are inverted from their inherited state;

9) Stopping criterion.

Generally, all of these specifications are constant across generations, but this need not necessarily be the case. There may be specific advantages to having some of these specifications vary within a single evolutionary sequence.

The details of the implementation can significantly affect the behavior and efficiency of the algorithm, particularly its speed of convergence. The fitness function need not be purely subjective, e.g., it can be based on cortical evoked potentials either alone or with subjective inputs. But if the fitness function used involves subjective comparisons by a user, it is important to limit N_g because a human listener cannot reasonably compare dozens of concurrent alternatives. A subjective fitness function is also 'expensive' in terms of time, which makes rapid convergence important. In general, the number of generations required for convergence rises with the number of genes per organism (N_b), so it is desirable to keep N_b as small as possible while still representing those MAP parameters which are most likely to influence performance.

Preferably, at each iteration the user is given the opportunity to flag MAPs to be saved for future consideration. In this way if the process 'stumbles' onto a particularly good MAP it can be saved either in step 302 or in step 318 for comparison against the eventual result of the evolution. This eliminates the risk of frustrating the user. If multiple runs are used, saved designs, or designs resulting from a first run, can be included in the initial population for a subsequent run.

Expert knowledge can be incorporated into the process in various ways. As noted above, the MAPs of the initial generation can be based upon clinical judgment. Also, specific parametric combinations known to be detrimental can be excluded from the universe of possible MAPs. Conversely, specific parametric combinations known to be beneficial can be condensed into a single 'parameter;' or occurrence of a specific value of one parameter may be used to override and dictate the value of a different parameter (e.g., any time the rate is > 2400 Hz, the number of channels is limited to 10). Finally, as the population evolves, the expert may serve as an auxiliary form of input to guide the evolution in particular directions. For example, the clinician, based upon a visual representation of the evolution of the parameters, may anticipate more efficient paths to an optimal region. This expert knowledge can then be used to help steer the update mechanism in the proper direction.

The method of the invention has the advantage that it can be automated, requiring no supervision by the audiologist. It may also be repeated periodically as the recipient becomes more experienced. Separate optimizations may be performed for specific classes of input signals (e.g., speech in quiet, speech in noise, music, etc).

In some instances, it may be desirable to 'freeze' the values of one or more parameters after several iterations, using the value of the intermediate MAPs resulting from the iterations. For example, if in step 302 while analyzing the current generation of MAPs it is that all the survivors of a generation correspond to a subset of parameters that are identical (e.g., all the survivors have the same rate, the same number of maxima and the same number of electrodes), then these parameters are frozen. This may be accomplished in several ways. The simplest approach is to save the parameter values in a separate memory, let the algorithm run its course, and, at the end, when the final generation is obtained, substitute some of the 'final' parameters, that is, the parameters corresponding to the final MAPs with the 'frozen' parameters obtained during iterations.

Another approach is to use a different set of MAPs with lower bit series. For example, if originally 10-bit MAPs are used for eight parameters, and after some iterations, three of the parameter values are frozen, then a new set of 8-bit MAPs is used for the algorithm. The shorter MAPs used to continue the algorithm may consist of a set of initial MAPs as discussed above, or may be derived from the intermediate MAPs.

Finally, the algorithm itself may be modified so that after some of the parameters are frozen, portions of the MAPs are not changed anymore, i.e., they are not subject to gene selection. Of course, this approach is easiest to implement for MAP configurations in which all or some of bits of the MAPs correspond to, or represent specific parameter.

In principle, the recipient could perform optimizations at home using signals of his or her own choosing (e.g., a spouse's voice).

Although the invention has been described with reference to particular embodiments it is to be understood that these embodiments are merely illustrative of the application of the principles of the invention. Numerous modifications may be made therein and other arrangements may be devised without departing from the spirit and scope of the invention.

We claim:

1. A method of fitting a cochlear implant to a patient comprising:

(a) executing a genetic algorithm to select values for a set of parameters to fit the implant, the genetic algorithm operating to generate successive generations of multiple groups of values for said parameter subset, and

(b) using patient feedback during execution of the genetic algorithm to determine the multiple groups of parameter subset values in successive generations.

2. A method of fitting a cochlear implant to a patient in accordance with claim 1 further including:

(c) selecting values for the parameters not included in said subset by a method that does not use a genetic algorithm.

3. A method of fitting a cochlear implant to a patient in accordance with claim 2 wherein said patient feedback involves selecting, without ranking, preferred groups of parameter values in one generation from which the groups of parameter values in the next generation are determined.

4. A method of fitting a cochlear implant to a patient in accordance with claim 3 wherein the values of said parameters are represented by a binary string of 6-12 bits.

5. A method of fitting a cochlear implant to a patient in accordance with claim 3 wherein there are 6-12 groups of parameter values in each generation.

6. A method of fitting a cochlear implant to a patient in accordance with claim 3 wherein the values of said parameters are represented by a string of bits, with different sub-strings of bits in said string representing values of respective parameters.

7. A method of fitting a cochlear implant to a patient in accordance with claim 6 wherein the parameters in said subset are related to rate, number of maxima and number of channels.

8. A method of fitting a cochlear implant to a patient in accordance with claim 3 wherein the values of said parameters are represented by a string of bits, some of the bits in said string being divided into separate sub-strings each of which represents the value of a respective parameter, and the others of the bits in said string identifying a predetermined group of parameter values.

9. A method of fitting a cochlear implant to a patient comprising the steps of:

(a) performing a genetic algorithm to select values for a subset of all the parameters for which values must be selected to fit the implant, the genetic algorithm operating to generate successive generations of multiple groups of values for said parameter subset, and

(b) based on the subjective listening judgment of the patient during execution of the genetic algorithm, selecting substantially less than all of the groups of values for said parameter subset in each generation and determining from them a larger number of groups of values for the next generation.

10. A method of fitting a cochlear implant to a patient in accordance with claim 9 wherein N groups of values for said parameter subset are determined for each generation, and a predetermined number of of said groups are selected in each generation for the determination of the N groups in the next generation.

11. A method of fitting a cochlear implant to a patient in accordance with claim 10 wherein said predetermined number is approximately N/2.

12. A method of fitting a cochlear implant to a patient in accordance with claim 9 wherein there are 6-12 groups of parameter subset values in each generation.

13. A method of fitting a cochlear implant to a patient in accordance with claim 9 wherein the values of said subset of parameters are represented by a string of bits, the string of bits being divided into separate sub-strings each of which represents the value of a respective parameter.

14. A method of fitting a cochlear implant to a patient in accordance with claim 13 wherein the string of bits for representing each group of values for the next generation is determined by combining parts of two different strings of bits that represent groups of values for the current generation.

15. A method of fitting a cochlear implant to a patient in accordance with claim 9 wherein the genetic algorithm is executed a fixed number of times to generate a fixed number of successive generations of multiple groups of values for said parameter subset, and a final group of values for the parameter subset is selected from the groups in the final generation.

16. A method of fitting a cochlear implant to a patient in accordance with claim 9 wherein a record is made of any group of values that the patient identifies as satisfactory in any generation, and a final group of values is selected from the groups in the final generation and those previously identified by the patient.

17. A method of fitting a cochlear implant to a patient in accordance with claim 9 wherein each generation of subset of parameter values are represented by a plurality of binary strings, each string defining a specific value for each parameter, wherein a lookup table is used to correlate each binary string to a corresponding set of parameter values.

18. A method of fitting a cochlear implant to a patient comprising the steps of:

(a) assigning a set of MAPs to a plurality of parameters, each MAP forming a string of binary bits and designating values for said parameters;

(b) executing a genetic algorithm on said set of MAPs by operating successive generations of MAPs , and

(c) using patient feedback during execution of the genetic algorithm to select a specified number of MAPs that survive each generation until a final generation is obtained.

19. The method of claim 18 wherein said final generation is obtained by repeating said algorithm a predetermined number of times.

20. The method of claim 18 further comprising testing successive generations of MAPs for predetermined criteria and stopping when said predetermined criteria has been met.

21. The method of claim 20 wherein said testing includes generating an indication of the diversity of said successive generation of MAPs and stopping when said diversity reaches a minimum value.

22. The method of claim 18 further comprising designating an initial generation to start said algorithm.

23. The method of claim 22 further comprising designating said initial generation arbitrarily.

24. The method of claim 23 further comprising testing an arbitrarily designated initial generation to determine if it meets predetermined criteria before starting the algorithm.

25. The method of claim 18 wherein said string includes between 6 and 12 bits.

26. The method of claim 18 wherein said string includes 8 bits.

27. The method of claim 18 wherein said string includes 10 bits.

28. The method of claim 18 wherein said parameters are selected from the group consisting of number of stimulation channels, stimulation rates, number of stimulation maxima, Q-value, FAT shift, T-level bump and filter settings.

29. The method of claim 18 wherein after some initial iterations of the genetic algorithm the values of some parameters is set and is not changed during the remaining iterations.

30. The method of claim 18 wherein said genetic algorithm includes:

(a) eliminating some MAPs from a current generation;

(b) pairing the remaining MAPs; and

(c) selecting bits from paired MAPs to form new MAPs.

31. The method of claim 30 wherein every generation has the same number of MAPs.

32. The method of claim 30 wherein within the MAPs of a new generation, some bits are arbitrarily inverted.

33. The method of claim 30 wherein half of the MAPs of the current generation are eliminated.

34. The method of claim 30 wherein MAPs are eliminated using input from the patient.

35. The method of claim 34 wherein MAPs are eliminated by allowing the patient to listen to speech through a processor using sequentially the parameters corresponding to each MAP with the patient selecting the MAPs that result in the clearest audible signals.

36. The method of claim 30 wherein MAPs are eliminated by determining a response of the hearing system of a patient to known stimulation through a processor using parameters defined by the MAPs.

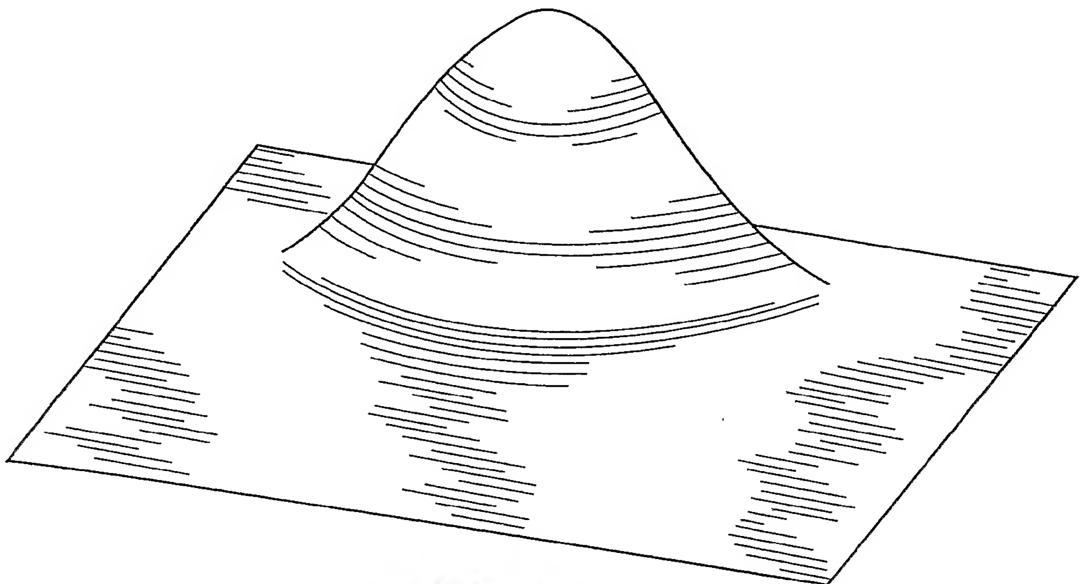


FIG. 1a

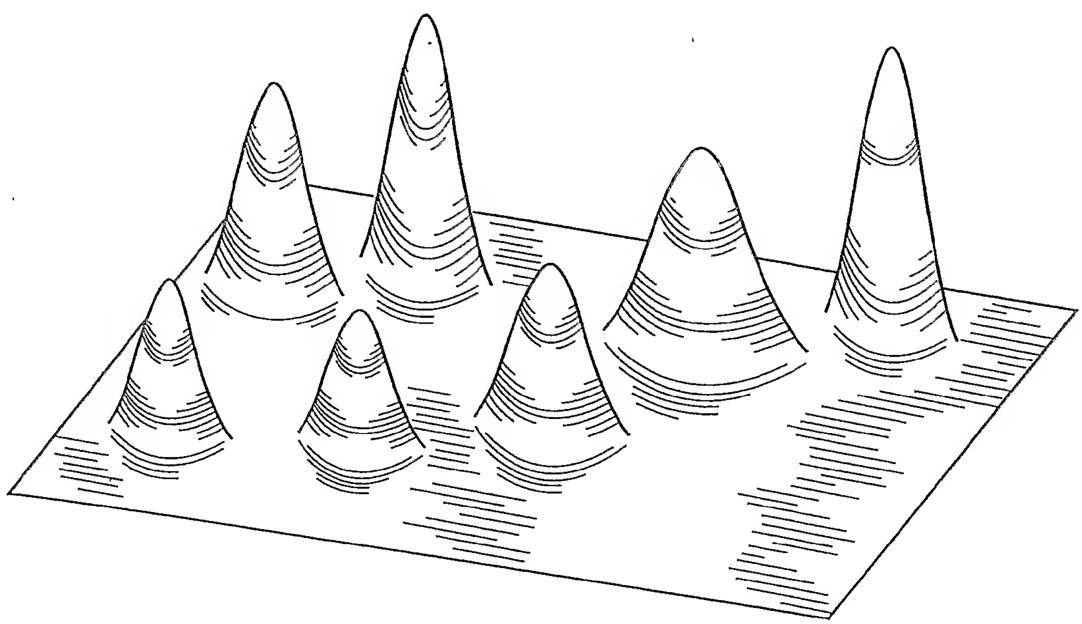
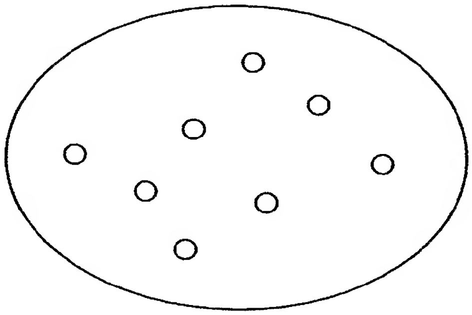
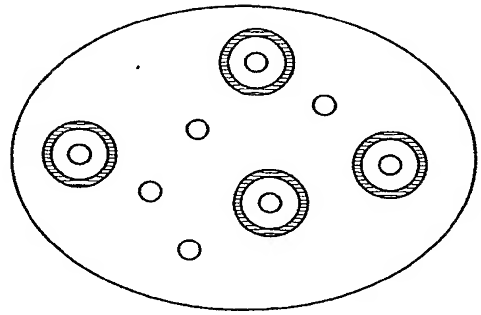


FIG. 1b



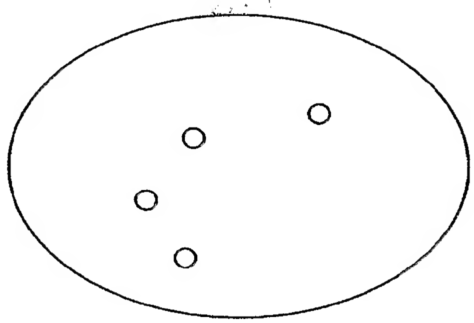
GENERATION 5
EVOLUTION SEQUENCE

FIG. 2a



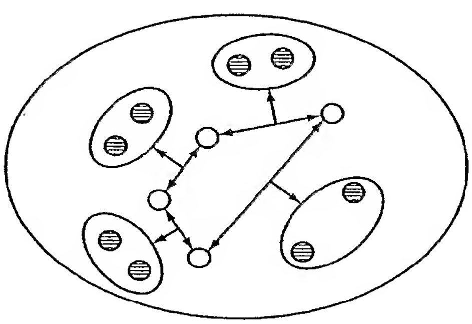
GENERATION 5
SELECTION

FIG. 2b



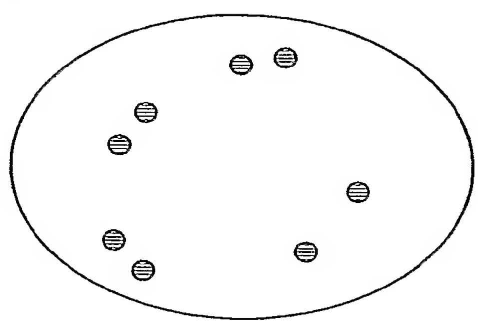
GENERATION 5
SURVIVAL OF
THE FITTEST

FIG. 2c



PAIRS OF PARENTS
PROCREATE

FIG. 2d



GENERATION 6
OFFSPRING FORM
NEXT GENERATION

FIG. 2e

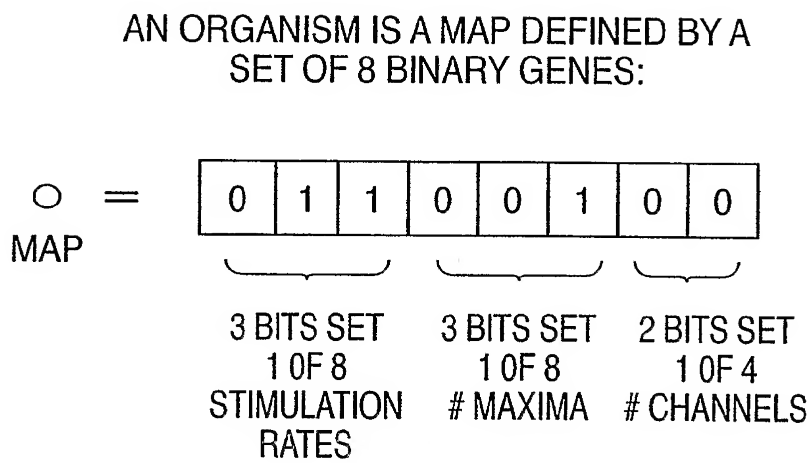

AN ORGANISM IS A MAP DEFINED BY A
SET OF 8 BINARY GENES:
O =
MAP
0
1
1
0
0
1
0
0
3 BITS SET
1 0F 8
STIMULATION
RATES
3 BITS SET
1 0F 8
MAXIMA
2 BITS SET
1 0F 4
CHANNELS

FIG. 3a

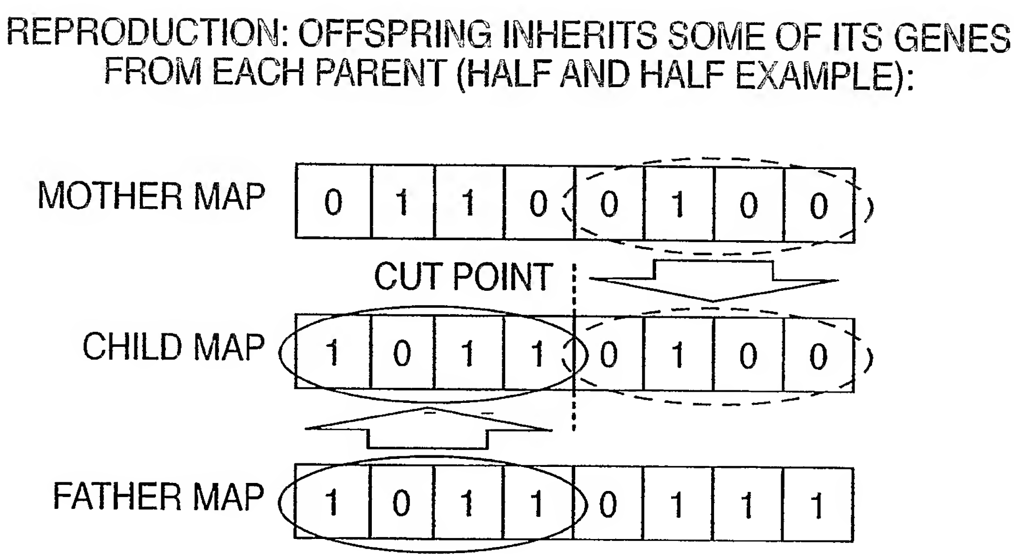

REPRODUCTION: OFFSPRING INHERITS SOME OF ITS GENES
FROM EACH PARENT (HALF AND HALF EXAMPLE):
MOTHER MAP
0
1
1
0
0
1
0
0
CUT POINT
CHILD MAP
1
0
1
1
0
1
0
0
FATHER MAP
1
0
1
1
0
1
1
1

FIG. 3b

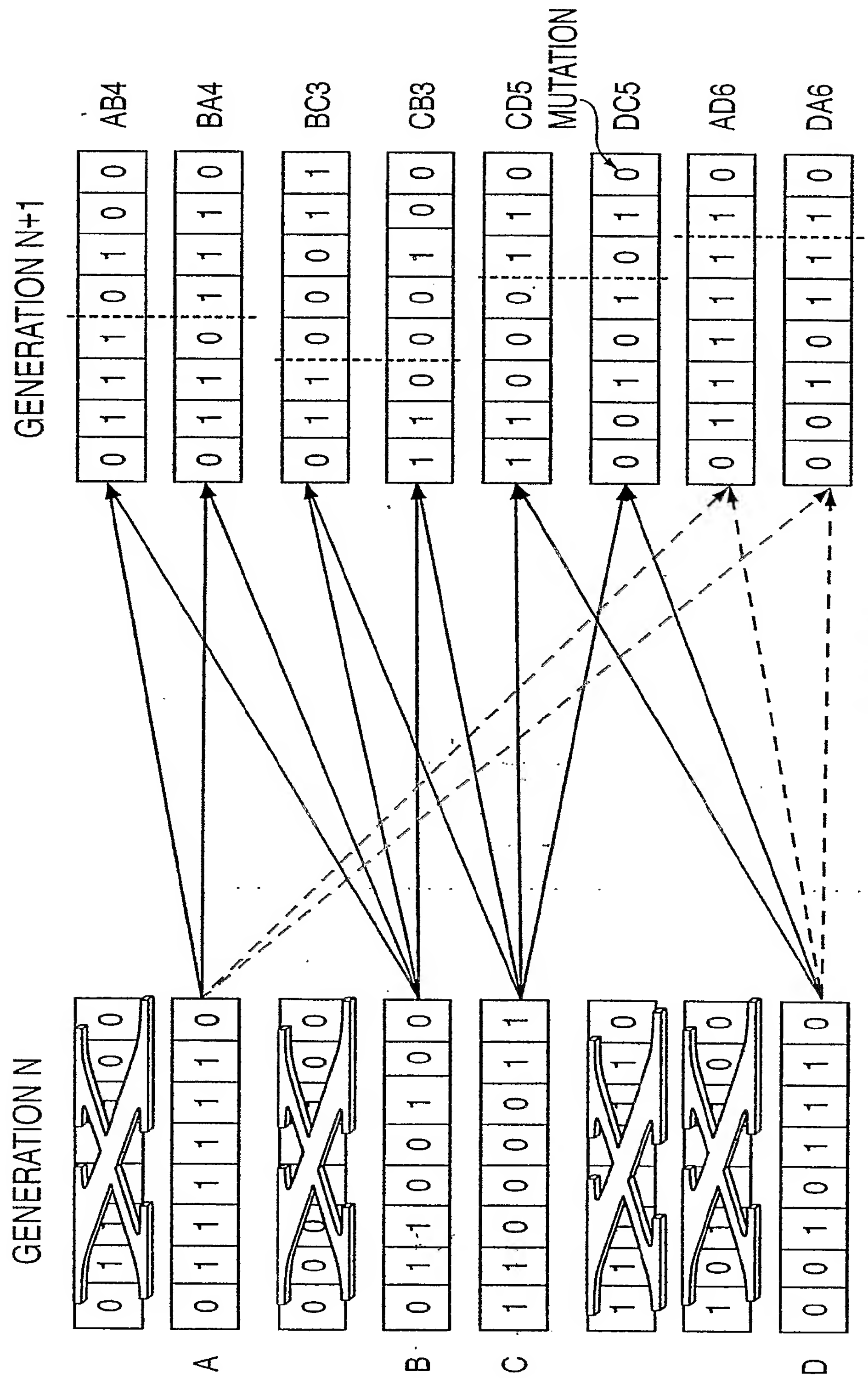

GENERATION N
GENERATION N+1
A
B
C
D
AB4
BA4
BC3
CB3
CD5
DC5
AD6
DA6
MUTATION

FIG. 3c

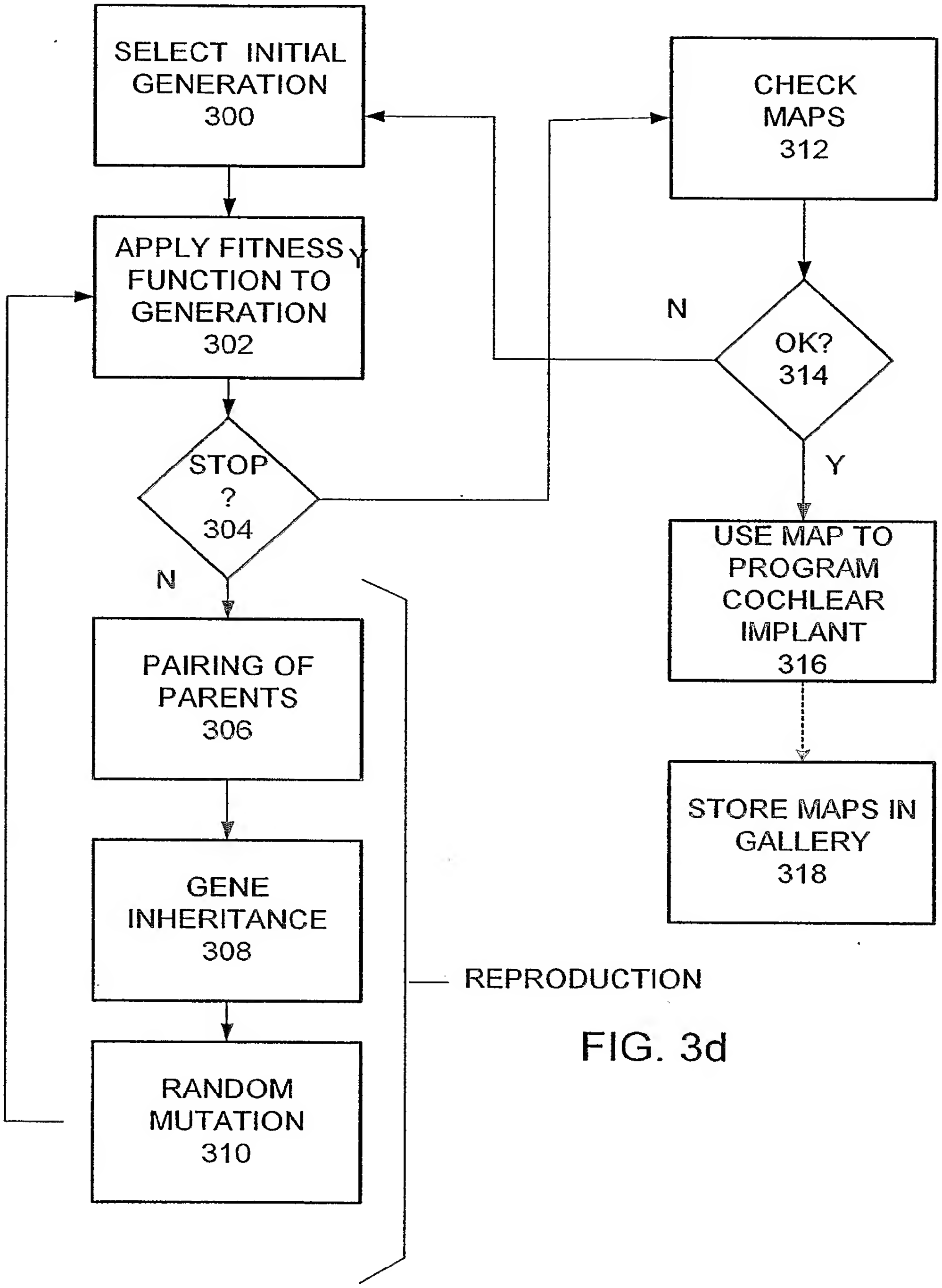
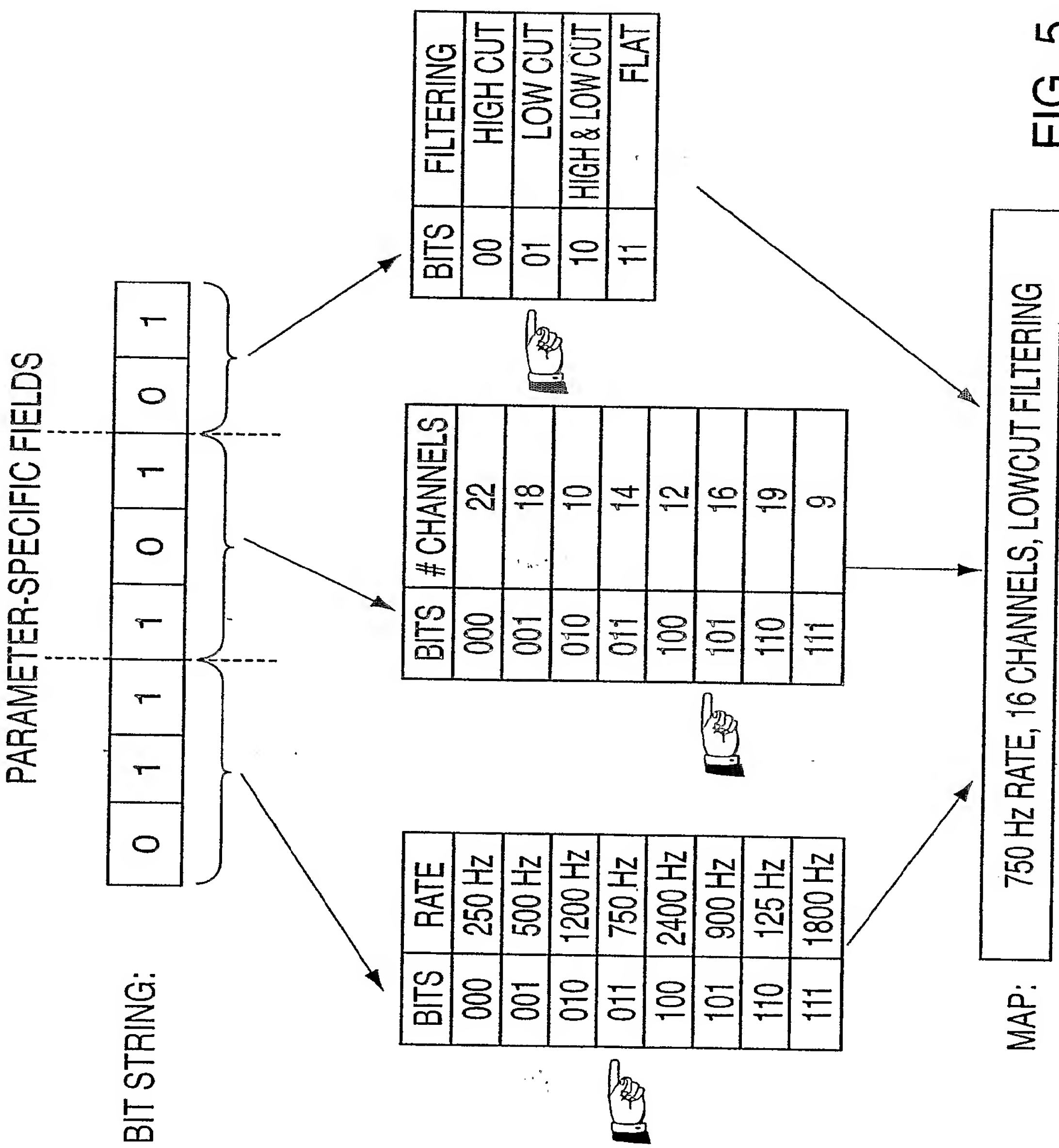

SELECT INITIAL GENERATION 300
APPLY FITNESS FUNCTION TO GENERATION 302
Y
STOP ? 304
N
PAIRING OF PARENTS 306
GENE INHERITANCE 308
RANDOM MUTATION 310
CHECK MAPS 312
N
OK? 314
Y
USE MAP TO PROGRAM COCHLEAR IMPLANT 316
STORE MAPS IN GALLERY 318
REPRODUCTION

FIG. 3d

BIT STRING	MAP PARAMETERS				
	RATE	# OF MAXIMA	# OF ELECTRODES	COMPRESSION (Q)	AUDIO FILTERING
00000000	250	4	22	20	FLAT
00000001	250	6	22	20	FLAT
00000010	250	8	22	20	FLAT
00000011	720	6	22	20	FLAT
00000100	1200	6	22	20	FLAT
00000101	720	8	22	20	FLAT
00000110	250	12	22	20	FLAT
00000111	250	16	22	20	FLAT
	119 OTHER LEGAL COMBINATIONS OF RATE, # OF MAXIMA, # OF ELECTRODES, COMPRESSION Q, AND AUDIO FILTERING				
01111111	250	4	10	30	HIGH CUT
10000000	250	4	22	20	LOW CUT
	126 OTHER LEGAL COMBINATIONS OF RATE, # OF MAXIMA, # OF ELECTRODES, COMPRESSION Q, AND AUDIO FILTERING				
11111111	250	4	10	30	HIGH CUT + LOW CUT

FIG. 4



BITS	RATE
000	250 Hz
001	500 Hz
010	1200 Hz
011	750 Hz
100	2400 Hz
101	900 Hz
110	125 Hz
111	1800 Hz

BITS	# CHANNELS
000	22
001	18
010	10
011	14
100	12
101	16
110	19
111	9

BITS	FILTERING
00	HIGH CUT
01	LOW CUT
10	HIGH & LOW CUT
11	FLAT

FIG. 5

COMBINATION - PARAMETER FIELDS & LOOKUP

BIT STRING:

0	1	0	0	0	0	1	1

BITS	RATE
000	250 Hz
001	500 Hz
010	1200 Hz
011	750 Hz
100	2400 Hz
101	900 Hz
110	125 Hz
111	1800 Hz

BITS	CHANNEL / FILTERING
00001	12 CHANNELS, HIGH-CUT FILTERING
00010	17 CHANNELS, HIGH-CUT FILTERING
00011	6 CHANNELS, FLAT FILTERING
00100	22 CHANNELS, LOW-CUT FILTERING
	26 OTHER UNIQUE CHANNEL / FILTERING COMBINATIONS
11110	10 CHANNELS, LOW-CUT FILTERING
11111	22 CHANNELS, FLAT-FILTERING

MAP: 1200 Hz RATE, 6 CHANNELS, FLAT FILTERING

FIG. 6

NUMBER OF CHNL	STIM. RATE	NO. OF MAXIMA	Q	FAT SHIFT	T-LEVEL BUMP	FILTERS
8 12 20	250 720 900 1200 1800 2400	6 8 12 16 20	10 20	DEFAULT SHIFT	DEFAULT BUMP	LOW B LOW CUT HIGH CUT LOW C HIGH C FLAT

Fig. 7

BINARY	NUMBER OF CHNL	STIM. RATE	NO. OF MAXIMA	Q	FAT SHIFT	T LEVEL	FILTERS
0000000000	20	250	8	10	1	1	1
0000000001	20	250	8	10	1	1	2
0000000010	20	250	8	10	1	1	3

Fig. 8

FREQ. INDEX	TABLE 6	TABLE 7	TABLE 8	TABLE 14	TABLE 15	TABLE 16
0	*188*	188	**188**	188	*188*	**188**
1	*313*	313	**313**	313	*313*	**313**
2	*438*	438	**438**	563	*563*	**563**
.	.	.	.	.	.	.
.	.	.	.	.	.	.
10	*1563*	1688	**1688**	3438	*4063*	**4813**
11	*1813*	1938	**1938**	4188	*5063*	**6188**
12	*.2063*	2188.	**2313**	5188	*6313*	**7938**
13	*2313*	2563	**2688**	6313	7938	
.	.	.	.	.		
.	.	.	.			
.	.	.	.			
20	*6063*	6938	**7938**			
21	6938	7938				
22	7938					

Fig. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US04/07400

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) : A61N 1/08
US CL : 607/057
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 607/057, 055, 056, 059; 600/559; 381/23.1, 312, 314; 128/920, 924, 925; 073/585

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
Please See Continuation Sheet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,953,112 A (WIDIN et al.) 28 August 1990 (28.08.1990), entire document.	1-36

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"O" document referring to an oral disclosure, use, exhibition or other means

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Date of the actual completion of the international search	Date of mailing of the international search report
16 July 2004 (16.07.2004)	27 AUG 2004

Name and mailing address of the ISA/US	Authorized officer
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Continuation of B. FIELDS SEARCHED Item 3:
EAST, MEDLINE, KOVEL, SCIENCE DIRECT, IEEE Xplore
search terms: genetic, algorithm, cochlear, generation, fitting, mutant, parent, evolution, audiologist, optimize, parameter, test, implant, MAP, ear.